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Cloud-Based Manufacturing: Old Wine in New Bottles?

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Abstract

Cloud-based manufacturing (CBM), also referred to as cloud manufacturing, is a form of decentralized and networked manufacturing evolving from other relevant manufacturing systems such as web- and agent-based manufacturing. An ongoing debate on CBM in the research community revolves around several aspects such as definitions, key characteristics, computing architectures, programming models, file systems, operational processes, information and communication models, and new business models pertaining to CBM. One question, in particular, has often been raised: *Is cloud-based manufacturing a new paradigm, or is it just old wine in new bottles?* Based on the discussion of the key characteristics of CBM, the derivation of requirements that an ideal CBM system should satisfy, and a thorough comparison between CBM and other relevant manufacturing systems, we provide supporting evidence that allows us to conclude that CBM is definitely a new paradigm that will revolutionize manufacturing.

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Keywords: cloud-based manufacturing; distributed manufacturing; cloud computing.

1. Introduction

In its initial application field of information technology (IT), cloud computing has proven to be a disruptive technology. It leverages existing technologies such as utility computing, parallel computing, and virtualization [1]. Some of its key characteristics include agility, scalability and elasticity, on-demand computing, and self-service provisioning [2]. Adapted from the original cloud computing paradigm, cloud-based manufacturing (CBM) is gaining significant momentum and attention from both academia and industry [3]. CBM is a form of decentralized and networked manufacturing based on many enabling technologies such as cloud computing, social media, the Internet of Things (IoT), and service-oriented architecture (SOA), all of which form the backbone of this new manufacturing paradigm [3]. An ongoing debate on CBM revolves around several aspects such as definitions, key characteristics, computing architectures, programming models, file systems, operational processes, information and communication models, and new business models pertaining to CBM. Although a number of definitions exist for CBM [3-8], few are widely accepted. Moreover, some prototype systems have been developed and are being tested in industry; however, whether or not these prototypes are truly CBM systems remains a question. Thus, a more thorough understanding of CBM requires a thorough comparison between CBM and other relevant manufacturing systems.

The main objective of this paper is to answer the following question: *Is cloud-based manufacturing a new paradigm or just old wine in new bottles?* In order to address this concern, this paper proceeds as follows. Section 2 introduces the evolution of manufacturing systems, including centralized and decentralized manufacturing systems. Section 3 introduces key characteristics of CBM and presents a requirements checklist that CBM systems should satisfy. Section 4 compares and contrasts CBM with other distributed

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manufacturing systems. Based on the comparison, Section 5 draws conclusions that finally answer the question initially posed.

2. Evolution of manufacturing paradigms

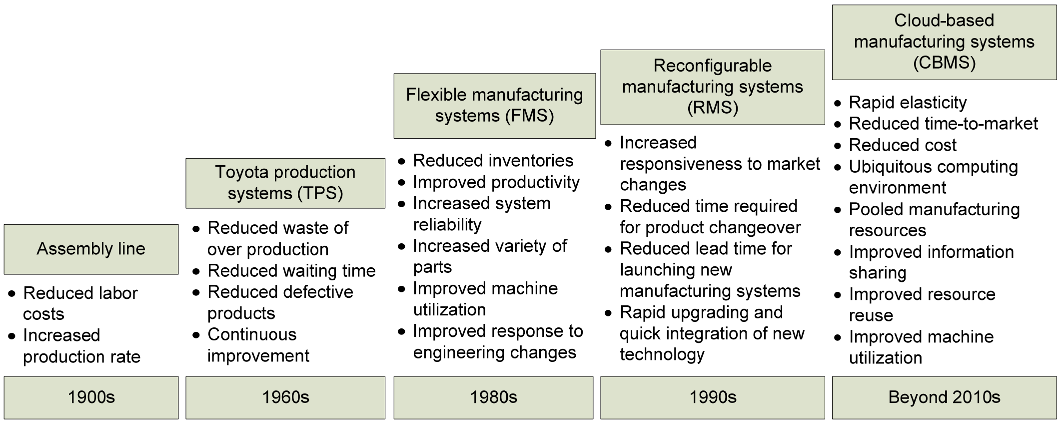

Fig. 1. Evolution of manufacturing systems.

Because of changing market demand and emerging technologies, manufacturing systems have undergone a number of major transitions [9-10]. Fig. 1 shows a brief evolution of manufacturing paradigms from the assembly line, to Toyota production systems (TPSs), to flexible manufacturing systems (FMSs), to reconfigurable manufacturing systems (RMSs), and to CBM. For example, Henry Ford created the first assembly line, in which interchangeable parts can be added to a product in a sequential manner to produce finished products more efficiently and cost-effectively. In the 1960s, to reduce manufacturing costs, TPSs, also known as just-in-time production systems, were devised. TPSs are characterized by a number of principles that assist in eliminating waste by reducing waiting time, inventory, and the number of defective products. In the 1980s, to yield new product variants, FMSs were developed, allowing for high functional flexibility. Specifically, the major advantage of an FMS is that it allows for variation in both parts and assemblies; however, its implementation is usually costly. According to Koren et al., "in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements, reconfigurable manufacturing systems (RMSs) are designed at the outset for rapid change in structure, as well as in hardware and software components" [11]. The key features of RMS include modularity, integrability, customization, convertibility, and diagnosability [12].

The previously stated manufacturing systems fall into the category of centralized manufacturing with significant changes in machine tools, manufacturing plant layouts, and business models. With the development of the Internet, distributed manufacturing systems have been increasingly adopted by industry; two major approaches for distributed manufacturing are web- and agent-based manufacturing systems. Web-based systems use the client-server architecture with the Internet to provide a light-weight platform for geographically dispersed teams to access and share manufacturing-related information via a web browser [13-14]. Likewise, with the increasing structural and functional complexity of web-based manufacturing systems, agent-based manufacturing systems aim at improving computational performance and communication using agents [15-16]. Agent-based manufacturing systems consist of agents (e.g., manufacturing cells, machine tools, and robots) exhibiting autonomous and intelligent behavior such as searching, reasoning, and learning. For example, an agent is an independent problem-solver capable of making decisions by interacting with other agents and its environment [17].

Table 1. Cloud-based manufacturing-related definitions.

Group	Definition
[3]	"Cloud manufacturing is a computing and service-oriented manufacturing model developed from existing advanced manufacturing models (e.g., application service providers, agile manufacturing, networked manufacturing, manufacturing grids) and enterprise information technologies under the support of cloud computing, the Internet of things (IoT), virtualization and service-oriented technologies, and advanced computing technologies."
[4]	"Cloud manufacturing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable manufacturing resources (e.g., manufacturing software tools, manufacturing equipment, and manufacturing capabilities) that can be rapidly provisioned and released with minimal management effort or service provider interaction."
[5]	"Cloud-based design and manufacturing (CBDM) refers to a service-oriented product development model in which service consumers are able to configure products or services as well as reconfigure manufacturing systems through Infrastructure-as-a-Service (IaaS), Platform-as-a-Service (PaaS), Hardware-as-a-Service (HaaS), and Software-as-a-Service (SaaS) in response to rapidly changing customer needs. CBDM is characterized by on-demand self-service, ubiquitous access to networked data, rapid scalability, resource pooling, and virtualization. The types of deployment models include private, public, and hybrid clouds."

Recently, with the emergence of cloud computing, CBM has become a promising manufacturing paradigm that will drive new manufacturing business models. Table 1 lists three of the existing definitions of CBM. Although each definition may focus on a unique aspect of CBM, all of them include common elements such as networked manufacturing, ubiquitous access, multi-tenancy and virtualization, big data and the IoT, everything-as-a-service (e.g., infrastructure-as-a-service, platform-as-a-service, hardware-as-a-service, and software-as-a-service), scalability, and resource pooling.

3. Characteristics and requirements for cloud-based manufacturing systems

According to the three existing definitions for CBM presented in Section 2, Table 3 lists some common key characteristics of CBM and compares CBM with other relevant distributed manufacturing paradigms, i.e., web- and agent-based manufacturing. As shown in Table 2, CBM provides significantly more benefits than web- and agent-based systems.

Table 2. Key characteristics of CBM and comparison to Web- and Agent-based manufacturing.

Characteristics	Web-based	Agent-based	Cloud-based
Scalability	×	×	×
Agility	×	×	×
High performance computing		×	×
Networked environment		×	×
Affordable computing			×
Ubiquitous access			×
Self-service			×
Big data			×
Search engine			×
Social media			×
Real-time quoting			×
Pay-per-use			×
Resource pooling			×
Virtualization			×
Multi-tenancy			×
Crowdsourcing			×
Infrastructure-as-a-service			×
Platform-as-a-service			×
Hardware-as-a-service			×
Software-as-a-service			×

Based on the key characteristics listed in Table 2, we have developed a requirements checklist that an ideal CBM system should satisfy, shown in Table 3. The purpose of the requirements checklist is to clearly define whether or not a manufacturing system is cloud-based. Each requirement is detailed as follows:

- Requirement 1 (R1): To connect individual service providers and consumers in the networked manufacturing setting, a CBM system should support social media-based networking services. Social media such as Quirky allows users to utilize/leverage crowdsourcing in manufacturing. In addition, social media does not only connect individuals; it also connects manufacturing-related data and information, enabling users to interact with a global community of experts on the Internet.
- Requirement 2 (R2): To allow users to collaborate and share 3D geometric data instantly, a CBM system should provide elastic and cloud-based storage that allows files to be stored, maintained, and synchronized automatically.

Table 3. A requirements checklist for CBM systems.

Requirement	Requirement description
R1.	Should provide social media to support communication, information and knowledge sharing in the networked manufacturing environment
R2.	Should provide cloud-based distributed file systems that allow users to have ubiquitous access to manufacturing-related data
R3.	Should have an open-source programming framework that can process and analyze big data stored in the cloud
R4.	Should provide a multi-tenancy environment where a single software instance can serve multiple tenants
R5.	Should be able to collect real-time data from manufacturing resources (e.g., machines, robots, and assembly lines), store these data in the cloud, remotely monitor and control these manufacturing resources
R6.	Should provide IaaS, PaaS, HaaS, and SaaS applications to users
R7.	Should support an intelligent search engine to users to help answer queries
R8.	Should provide a quoting engine to generate instant quotes based on design and manufacturing specification

- Requirement 3 (R3): To process and manage large data sets, so called big data, with parallel and distributed data mining algorithms on a computer cluster, a CBM system should employ an open-source software/programming framework that supports data-intensive distributed applications [18]. For example, MapReduce is one of the most widely used programming models in cloud computing environments, as it is supported by leading cloud providers such as Google and Amazon [19].
- Requirement 4 (R4): To provide SaaS applications to customers, a CBM system should support the multi-tenancy architecture. Through multi-tenancy, a single software instance can serve multiple tenants via a web browser. According to Numecent, a cloud platform, called Native as a Service (NaaS), is developed to deliver native Windows applications to client devices. In other words, NaaS can “cloudify” CAD/CAM software such as Solidworks without developing cloud-based applications separately [20]. With such a multi-tenant platform, such programs can be run as if they were native applications installed on the user’s device.
- Requirement 5 (R5): To allocate and control manufacturing resources (e.g., machines, robots, manufacturing cells, and assembly lines) in CBM systems effectively and efficiently, real-time monitoring of material flow, availability and capacity of manufacturing resources become increasingly important in cloud-based process planning, scheduling, and job dispatching. Hence, a CBM system should be able to collect real-time data using IoT technologies such as radio-frequency identification (RFID) and store these data in cloud-based distributed file systems.
- Requirement 6 (R6): To implement the service-oriented architecture model in manufacturing, a CBM system

should provide for users X-as-a-service (everything as a service) applications such as IaaS, PaaS, HaaS, and SaaS.

- Requirement 7 (R7): To assist users to find suitable manufacturing resources in the cloud, a CBM system should provide an intelligent search engine to help answer users' queries.
- Requirement 8 (R8): To streamline workflow and improve business processes, a CBM system should provide an online quoting engine to generate instant quotes based on manufacturing specifications.

4. Comparing cloud-based manufacturing with traditional distributed manufacturing paradigms

In addition to the comparison presented in Section 3, the differences and similarities between CBM and web- and agent-based systems will be articulated from a number of perspectives, including (1) computing architectures, (2) data storage, (3) operational processes, (4) information and communication, (5) business models, and (6) programming models.

4.1. Computing architecture

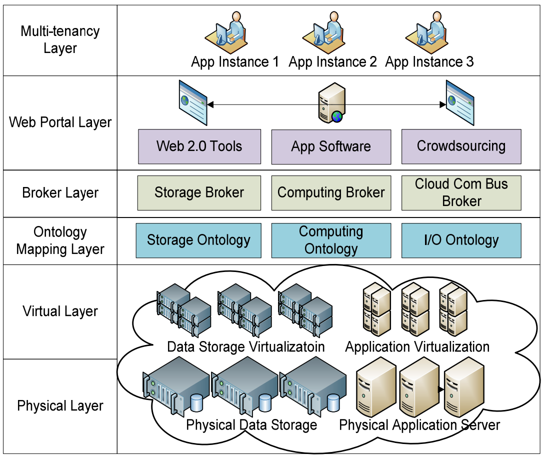

Fig. 2. A computing architecture for CBM systems.

From a computing perspective, the difference between web- and agent-based applications and cloud-based applications is two-fold: multi-tenancy and virtualization. Fig. 2 illustrates a unified computing architecture for CBM systems that is distinguished from web- and agent-based design and manufacturing systems. As previously stated, in the proposed computing architecture, multi-tenancy enables a single instance of the application software to serve multiple tenants. To share computing and IT resources in cloud computing, multi-tenancy is the most fundamentally used technology for its security and cost efficiency. In addition, as shown in the virtual layer in Fig. 2, virtualization can improve the efficiency and availability of computing and IT resources by re-allocating hardware dynamically to applications based on their need. Virtualization enables enterprises to separate engineering software packages, computing resources, and data storage from physical computing hardware as well as to support time and resource sharing.

4.2. Data storage

From a data storage perspective, with regard to web- and agent-based design and manufacturing, product-related data are stored at designated servers, and users know where these data are as well as who is providing them. However, with regard to CBM, networked enterprise data are stored not only in users' computers, but also in virtualized data centers that are generally hosted by third parties (see the virtual and physical layers in Fig. 2). Physically, these data may span across multiple servers. In other words, the users may neither exactly know who the service providers are nor where the data are stored. However, the data may be accessed through a web service application programming interface (API) or a web browser. The advantages of cloud-based data storage are: (1) cloud-based data storage provides users with ubiquitous access to a broad range of data stored in the networked servers via a web service interface; (2) data storage can easily scale up and down as needed on a self-service basis; (3) users are only charged for the storage they actually use in the cloud.

4.3. Operational processes

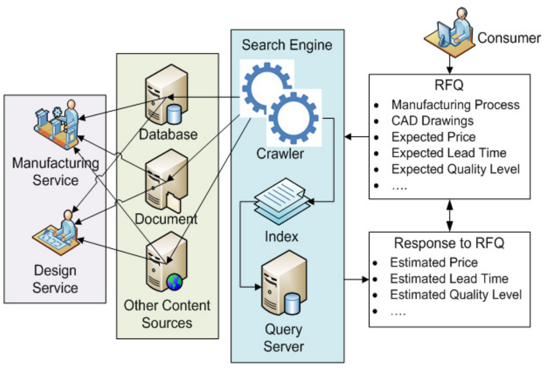

Fig. 3. A crowdsourcing process for RFQs in CBM systems.

From an operational process perspective, CBM can leverage the power of the crowd through crowdsourcing. For instance, CBM enables service consumers to quickly and easily locate qualified service providers offering manufacturing services such as CNC machining, injection molding, casting, or 3D printing through a crowdsourcing process. Fig. 3 illustrates the crowdsourcing process, which enables consumers to submit requests for quotes (RFQs) to a search engine and receive a list of qualified service providers. The search engine consists of a crawler, indices, and query servers. The crawler gathers manufacturing-related data (e.g., process variables, machine specifications) from databases, document servers, and other content sources, and it stores them in the index. The index ranks these data based on metrics (e.g., price, quality, and geographic location) specified by the users. A query server is the front end of the search engine; it delivers to consumers the results of a search query as a response to the RFQs; the results are based on the specifications such as expected prices, lead times, and quality levels. However, with regard to web- and agent-based systems, it is not feasible to implement such a computationally expensive crowdsourcing platform that connects service consumers and providers worldwide. Moreover, in comparison with commercial quoting systems such as Quickparts.com and MFG.com, the proposed crowdsourcing platform in CBM can not only conduct quoting for manufacturing services such as rapid prototyping, injection molding, and casting, but also conduct manufacturing and computing resource allocation, and scheduling activities. Further, in contrast with existing 3D printing services where users upload design files and print objects from a single site, CBM allows users to print their designs at any 3D printer in the cloud rather than at one particular site.

4.4. Information and communication

From a machine-to-machine communication perspective, CBM employs the IoT (e.g., RFID), smart sensor, and wireless devices (e.g., smart phone) to collect real-time manufacturing-related data as shown in Fig. 4. Because the IoT and embedded sensors can capture events (e.g., inventory level) and represent physical objects (e.g., machine tools) in digital form, communication in CBM enable a seamless flow of data between machines or things. However, such communication cannot be provided in web- and agent-based manufacturing systems because of their limited computing capabilities. In addition, from a human-to-human communication perspective, the use of web 2.0 technologies (see the web portal layer in Fig. 3) in developing web portals for CBM systems allows users to be better connected and to harness the power of social media. In web- and agent-based systems, users cannot exchange data and gather valuable feedback about their products effectively and efficiently.

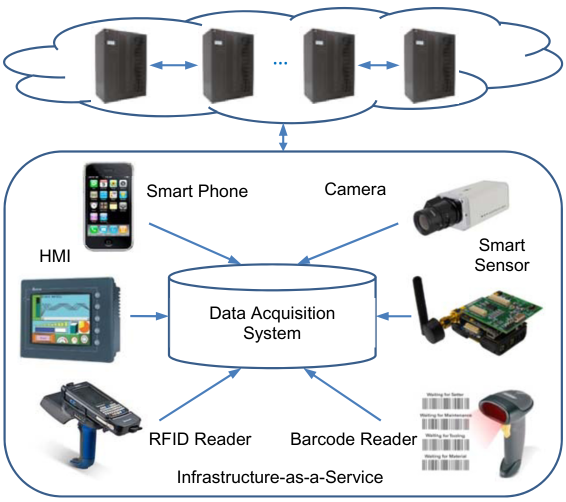

Fig. 4. Information and communication in CBM systems.

4.5. Business model

From a management perspective, the significant difference between CBM and web- and agent-based manufacturing is that CBM involves new business models; but web- and agent-based manufacturing paradigms do not. That is, CBM does not simply provide new technologies; it also involves how manufacturing services can be delivered (e.g., IaaS, PaaS, HaaS, and SaaS), how services can be deployed (e.g., private cloud, public cloud and hybrid cloud), and how services can be paid for (i.e., pay-per-use). For example, a key driver of CBM is the pay-per-use model that has the potential to reduce up-front investments on IT and manufacturing infrastructure for small- and medium-sized enterprises (SMEs). Instead of purchasing manufacturing equipment and software licenses, CBM users can pay a periodic subscription or utilization fee with minimal upfront costs. Likewise, scalability and elasticity allow users to avoid over purchase of computing and manufacturing capacities.

4.6. Programming model

From a programming model perspective, MapReduce, a parallel programming model, enables CBM systems to process large data sets which web- and agent-based manufacturing systems are not able to deal with. One of the most well-known open source implementations of the MapReduce model is Hadoop. Similar to other parallel programming models, Hadoop divides computationally extensive tasks into small fragments of work, and each work unit is processed on a computer node in a Hadoop cluster [21]. The MapReduce framework is implemented through two core processes named Map and Reduce. Specifically, in a Map process, a master node receives an input task, divides it into smaller sub-tasks, and distributes them to worker nodes. The worker nodes process the smaller sub-tasks, and send the answer back to the master node. In a Reduce process, a master node receives the answers of all the sub-tasks and combines them to generate the result of the original task. Such a parallel programming model enables CBM to handle big data generated in manufacturing.

5. Conclusion

In this paper, we presented the existing definitions for CBM and the common key characteristics of CBM, defined a requirements checklist that an ideal CBM system should satisfy, and compared CBM with relevant manufacturing systems from a number of perspectives. Specifically, CBM is characterized by scalability, agility, high performance and affordable computing, networked environments, ubiquitous access, self-service, big data, search engine, social media, real-time quoting, pay-per-use, resource pooling, virtualization, multi-tenancy, crowdsourcing, IaaS, PaaS, HaaS, and SaaS. Thus far, a few prototype systems achieved some functions in the requirement checklist; however, none of the existing systems satisfies all the requirements that we defined. The requirement checklist could serve as a benchmark for developing future CBM systems. Moreover, CBM is distinguished from web- and agent-based manufacturing from the perspectives of computing architecture, data storage, operational process, information and communication, business model, and programming model.

Finally, in response to the question initially posed, *whether or not cloud-based manufacturing is a new paradigm or just old wine in new bottles*, we concluded that cloud-based manufacturing is definitely a new paradigm that will revolutionize manufacturing, although cloud-based manufacturing is the result of evolution and adoption of existing technologies and manufacturing paradigms.

Meanwhile, the following questions remain open for investigation:

- What types of manufacturing services are suitable to move to the cloud?
- What types of companies are suitable to adopt CBM?
- What strategies or business models should be used by service providers and consumers?

As a result, to bridge the gap between the current research progresses and the vision for CBM, several directions for future research include the design and assessment of business models, cost-benefit analysis, and case studies for CBM.

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